CHAPTER TWO:
IMPACTS OF RECREATIONAL BOATING & PWC USE

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Recreational boating raises a number of issues for coastal resource managers and the public, including noise complaints, safety concerns and various environmental impacts. Although much information is available about these issues, relatively little is known about PWC-specific impacts or how they compare to those of more traditional vessels. This lack of information impairs the development of scientifically-sound resource policy and undermines the effectiveness of PWC management initiatives.

To rectify this, this section of the PWC Management Guide comprehensively reviews the scientific literature that does exist regarding PWC impacts. It discusses PWC use in the general context of recreational boating and, where appropriate, distinguishes between impacts that are unique to PWC and those that are relevant to other types of motorized vessels. This section also addresses the scientific uncertainties, data gaps and widespread misinformation that managers must contend with. Finally, it suggests important points to be considered as management alternatives are selected and strategies are developed.

2.1 NOISE

Physically speaking, noise is a measurement of sound (Box 1) and is a function of three variables: loudness, pitch and temporal variability (Komanoff and Shaw 2000).

Box 1. The Physics of Sound

Sound is a form of mechanical energy transmitted by rapid pressure (P) changes in an elastic medium, such as air or water. Acoustic pressures exhibit a huge and dynamic range, making them difficult to manage mathematically. Therefore, they are usually converted into a scale of decibels (dB) using the logarithmic equation:

$$dB= 20 \log (P/(2x10^{\wedge}-5)$$

When using this scale, it is important to note that separate sounds cannot be directly added to calculate a cumulative sound. Rather, the dB values must be converted back into acoustic pressures, added and then converted back into dB. Therefore, relatively small changes in dB ratings correspond to significant changes in sound (Komanoff and Shaw 2000).

Sound waves travel through seawater at approximately 1480 m/s and through air at about 331 m/s. As sound travels through these media, its intensity decreases due to spreading, scattering and/or absorption. This decrease is proportional to the given power of the distance between the source of the sound and the receiver. This corresponds to a sound reduction of 5dB (over water) to 6dB (over land) for each doubling of distance between the source and receiver of the sound (Garrison 1999, Gross 1993).

Loudness, which corresponds to the amplitude of a sound wave, is the difference between atmospheric pressure (without sound) and total pressure (with sound). It is measured in decibels and is the most common variable examined in noise issues.

Pitch, measured in Hertz (Hz), corresponds to wave frequency and is the rate at which a sound vibrates. In seawater, sound absorption is proportional to the square of sound frequency; therefore, high frequency sounds are absorbed quickly and don't travel as far through the water as low frequency sounds (Garrison 1999).

Temporal variability refers to the changing nature of noise patterns and can be described as continuous, fluctuating, intermittent or impulsive (see Table 1). Regardless of their relative noise level, fluctuating noises tend to be the most annoying because they penetratingly attract the hearer's attention and are difficult to "tune out."

TABLE 1. Types of Noise

Type	Characteristics	Example
Continuous	long duration; constant noise level	*waterfall*
Fluctuating	long duration; variable noise level	*freeway traffic*
Intermittent	short duration	*ringing telephone*
Impulsive	extremely short duration; loud	*gunshot*

Noise, or "unwanted sound," threatens public health and welfare by contributing to hearing loss and stress and by interfering with human activities such as thought, communication and sleep. Noise also detracts from environmental quality by polluting peace or serenity and by disturbing sensitive wildlife (US EPA 1974).

2.1.1 PWC and Noise

Noise is a ubiquitous complaint among beach-goers, waterfront property owners and traditional boaters who express their dislike of the high-pitched whine of PWC. Environmental advocates who contend that PWC noise compromises the integrity of marine and coastal environments by degrading quality of life, destroying recreational experiences and threatening wildlife, also highlight noise issues. PWC industry officials, on the other hand, emphasize that technological innovations such as baffles, insulation and resonator-equipped mufflers have significantly reduced PWC noise and that newer models are two to eight times quieter than older ones (PWIA 2000a). Their claims are backed by studies suggesting that, under analogous operating conditions, PWC are no louder than similar motorized vessels (Noise Unlimited 1995) and that PWC comply with all existing noise regulations.

According to the National Pollution Clearinghouse (NPC), PWC compliance with decibel regulations is a moot point. The NPC maintains that PWC have unique design and use characteristics that make them more annoying than other motorized vessels. For example, by continually leaving and reentering the water, PWC create rapid cycles of variable noise that disturb humans and wildlife. The repetitive smacking of PWC hulls against the water and the tendency of PWC operators to circle about the same location for extended periods of time also exacerbate PWC noise (Komanoff and Shaw 2000). For these reasons, many environmental groups charge that PWC use in near-shore areas subjects public beaches and habitat areas to excessive noise. They argue that more stringent PWC regulations are necessary to protect sensitive wildlife species and to maintain public health and welfare (Bluewater Network 1998, Martin 1999, NPCA 1999).

The Personal Watercraft Industry Association (PWIA), on the other hand, emphasizes the need for public waterways to accommodate a variety of users. Although it sympathizes with public concerns, the PWIA advocates for management strategies that fairly address the noise impacts of PWC and other motorized vessels. Specifically, the PWIA endorses the use of shoreline sound measurement laws, the establishment of slow/no-wake zones and the development of educational programs that promote socially-responsible and environmentally-sensitive PWC use (PWIA 2000b).

2.1.2 Management Considerations

- Noise is a function of loudness (dB), pitch (Hz) and temporal variability. While most new PWC models meet or exceed existing noise regulations, the high-pitched whine and operational behaviors associated with PWC continue to make them more annoying to many people.

- Since PWC have shallow drafts and lack propellers, they can operate at much higher speeds closer to shore than other types of motorized vessels. Therefore, in certain places or given certain operational behaviors, PWC-related noise may have a greater impact on wildlife and coastal visitors than other vessels.

- Buffer zones can be used to protect sensitive wildlife species and to minimize the disturbance that PWC cause to shorefront property owners, beachgoers and other coastal resource users.

- Researchers need to address the following data gaps and scientific uncertainties:

  - How wildlife species respond to PWC noise and how these responses vary over time.

  - The effect of PWC noise on the experience and satisfaction of coastal visitors.

  - The effectiveness of setback-distances and buffer zones at mitigating noise impacts.

2.2 SAFETY

In contrast to recreational boating issues that are linked to an increasing number or diversity of vessels on the water (i.e., overcrowding and multiple-use conflicts), safety issues rarely correlate to overall boating levels. In fact, research shows that most boating-related accidents, injuries and fatalities are linked to irresponsible and inappropriate vessel use rather than to the number of vessels on the water (American Red Cross 1991; NTSB 1998). Congress addressed this issue in 1971 by passing the Safe Boating Act, which expanded the USCG's role in supervising public waterways and enhanced its ability to improve recreational boating safety. Despite this federal action, however, many local and state law enforcement agencies continue to struggle with maintaining a safe recreational boating environment.

In recent years, this struggle has been exacerbated by notable increases in PWC use. PWC have certain characteristics that may make them more difficult to control than other vessels, especially for young or inexperienced riders (Williams 1996). These characteristics, combined with the thrill-seeking behavior of some PWC riders, give rise to distinct differences in the cause and nature of PWC safety incidents (American Academy of Pediatrics 2000; Branch *et al.* 1997; Clarke 2000; Hamman 1993). Moreover, they draw negative attention from safety officials, law officers and much of the boating public and have resulted in the implementation of PWC-specific restrictions throughout the country.

Despite these safety concerns, it is difficult to ascertain whether or not PWC pose a more eminent threat than other vessels. Vessel-specific accidents and injuries cannot be quantified because of insufficient reporting and incomplete accident and injury data makes it difficult to estimate, much less compare, the relative safety of different vessel types (NTSB 1998). Nonetheless, PWC are widely perceived to be a threat to public safety and this perception continues to be a driving force behind many PWC management initiatives.

2.2.1 PWC Design Characteristics

As previously noted, many of the high-performance design characteristics that make PWC appealing to ride also make them relatively dangerous and difficult to control. For example, PWC can accelerate rapidly and can travel across the water at very high speeds. They can also turn abruptly and weave through heavily congested boat traffic. Despite this maneuverability, PWC can be difficult to slow, stop or reverse. In fact, the only way to stop most PWC is to lay off the throttle and coast, which can be precarious when operating a PWC near other vessels or obstacles (Bluewater Network 1998; NPCA 1999). Stability can also be problematic for PWC operators. Older, smaller PWC models may be less stable than other vessels and may capsize when the operator falls off, thereby putting the operator at risk of drowning or being hit by a passing vessel (NPCA 1999). Finally, many PWC lack "off-throttle steering" so the vessel can only be turned if the engine is receiving sufficient power. This power-dependent steering mechanism is counterintuitive to most boaters and may contribute to PWC collisions (Bluewater Network 1998; NPCA 1999; NTSB 1998).

PWC manufacturers have addressed many of these design-related safety concerns. First, most new PWC models are larger, heavier and more stable. They do not leave the water as frequently as older models and are relatively difficult to capsize. Second, many newer PWC models have highly responsive reversible throttles that can be used to slow or maneuver the vessel. Many new models also have secondary steering mechanisms that enable riders to control the vessel if the throttle is disengaged. Third, all newly manufactured PWC models are equipped with mandatory "kill-switches." These switches are linked to the driver's wrist via a lanyard and automatically cut the power to the engine if the driver falls from the vessel (PWIA 2000).

Marine manufacturers have also partnered with government to reduce the speed at which PWC are designed to operate. Current government-industry recommendations state that new, factory-equipped PWC should not exceed a speed of 65 mph and various regulations have been proposed to prohibit the modification of PWC engines. Moreover, PWC manufacturers and their associates actively promote safe vessel operation by creating and distributing instructional brochures, manuals and videos (Martin 1999; PWIA 2000).

2.2.2 PWC Operational Behavior

Despite improvements to PWC design and safety, the improper, careless and inconsiderate behavior of some operators continues to be an issue for safety officials, boaters and marine resource users. For example, PWC riders launching or operating near public beaches can jeopardize swimmers and annoy beachgoers, while riders zig-zagging through congested waters or jumping boat wakes increase the likelihood of collisions, injuries and property damage. Although occurrences of these behaviors have not been quantified and are not unique to these vessels, but the operational behaviors of PWC riders have been closely scrutinized in recent years.

Boating safety studies show that, depending on state-specific boating education requirements, PWC operators may be lacking adequate boating education and experience. For example, the National Transportation Safety Board (NTSB) reports that over 80% of boaters and PWC users have never received any type of boating instruction (1998) and the American Red Cross reports that PWC use is highest among boaters with little or no experience (1991). This inexperience is due, in part, to the fact that PWC are relatively easy for aspiring boaters to access. According to research, PWC are more likely to be rented or borrowed than any other vessel and almost half of PWC renters have operated a PWC only once or never (Mangione *et al*. 2000).

PWC riders are often singled out because of the manner in which they operate their craft. For example, some riders travel at excessive or inappropriate speeds and many tend to ride in groups, with multiple riders on each craft. PWC operators can also perform stunts such as racing, spinning, spraying, wave jumping and weaving through vessel traffic (Bluewater Network 1998; NPCA 1999). These behaviors may contribute to PWC collisions, as well as the number and severity of subsequent injuries (Clarke 2000). While some contend that this type of behavior is typical of PWC users, others maintain that most riders are safe and courteous and that, in general, PWC operators are no more dangerous than other boaters.

Although the extent of irresponsible PWC use is not documented, there is clearly a need for safe operating practices to be followed. To this end, PWC manufacturers, associates and riders are actively trying to promote safe and responsible PWC use. In particular, the Personal Watercraft Industry Association (PWIA) dedicates significant time and resources to publish educational materials, endorse operator "codes of ethics", facilitate regulatory enforcement and develop safety protocols for PWC-rental operations.

2.2.3 PWC Accidents and Fatalities

PWC-related accidents and fatalities can be differentiated from other boating incidents in several ways (American Academy of Pediatrics 2000; American Red Cross 1991; Branche *et al.* 1997; NTSB 1998). For example, most traditional boating accidents occur when a vessel capsizes or a person falls overboard but most PWC accidents involve collisions. These collisions typically involve two or more vessels (often two or more PWC) and occur when riders are operating too close to one another. This spatially concentrated operation does not afford PWC riders enough time to react to each other's speed or directional changes and often results in personal injury and/or property damage (Branche *et al.* 1997; NTSB 1998).

Differences between boating and PWC-related accidents give rise to differences between boating and PWC fatalities. For instance, most boating fatalities are due to drowning, especially if the victim is not wearing a personal floatation device (PFD). Since PWC riders are more inclined than other boaters to wear PFDs (NTSB 1998), few PWC fatalities entail drowning. Instead, most PWC fatalities are due to blunt trauma sustained by a victim following a collision with the water, a fixed object or another vessel. Trauma-related PWC fatalities typically involve contusions and lacerations to the head, face and upper body (American Academy of Pediatrics 2000; Branche *et al.* 1997; NTSB 1998).

There are several other notable distinctions regarding PWC-related accidents and fatalities. First, most PWC incidents occur on either borrowed or rented vessels and tend to occur during the first hour of operation. Second, most PWC incidents occur while the operator is cruising, as opposed to wake jumping or spinning, and they typically occur at moderate speeds (i.e., below 30 mph). Third, most PWC incidents occur when riders are alone on a vessel. Accident rates tend to decrease significantly when two passengers are on board and very few accidents occur when three or four passengers are riding a single vessel. Finally, alcohol use tends to be substantially lower in PWC incidents than in boating ones (Branche *et al.* 1997; NTSB 1998).

2.2.4 Comparing Vessel Safety Data

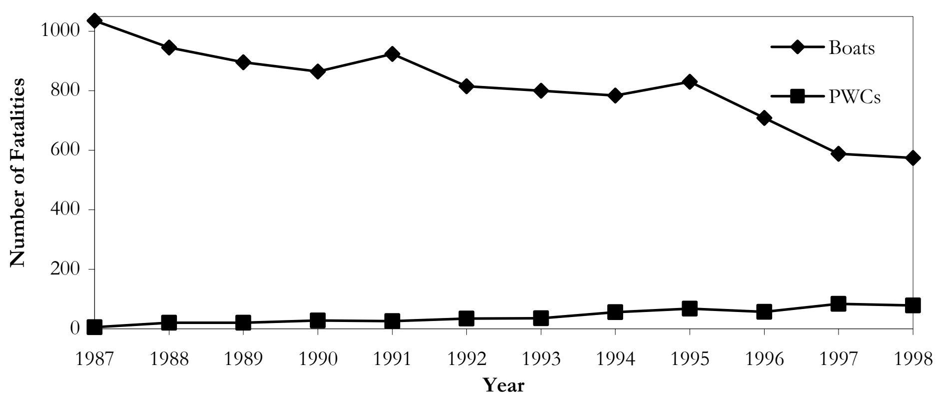
Definitive information on whether PWC have disproportionately high accident and fatality rates compared to their numbers on the water is unavailable at this time. Boating safety reports often contradict one another and make it difficult to determine if PWC are more dangerous than other vessels. These contradictions are due to inaccurate and/or insufficient reporting, as well as an overall lack of vessel exposure or use data.

Federal regulations require that a boating accident be reported to state boating officials if there is: 1) loss of life, 2) personal injury requiring more than basic first aid medical treatment, 3) property damage in excess of $2000 or the complete loss of a vessel and/or 4) the disappearance of any passenger (USCG 1998). However, boating safety experts suspect that a large number of accidents do meet these criteria but are not reported to the appropriate officials. For example, accidents resulting in property damage but not injury may only be reported to insurance companies, whereas accidents involving injury but not property damage may only be reported to hospital officials. In either case, the accident is not reflected in boating safety data (NTSB 1998). Insufficient reporting makes is difficult to accurately quantify the number of boating accidents that occur each year and, in turn, to compare the relative accident rate of different vessel types.

Boating accident comparisons can also be problematic because few safety reports record exposure or use data such as hours of operation. Since a vessel that is used for longer periods of time (i.e., more days/year or more hours/day) will have a higher chance of being involved in an accident, this data is necessary to compare relative accident rates among different vessels (NTSB 1998). Some boating surveys indicate that PWC are used for shorter periods of time than other vessels (Mangione *et al*. 2000) but site-specific analysis is necessary to determine relative vessel usage in a given area.

Due to the discrepancies of boating accident data, many experts suggest that boating fatality data is a better indicator of relative vessel safety. Fatality reporting tends to be highly accurate and, in general, fatality data is more complete and less skewed than accident data.

Table 2. Recreational Boating Fatalities



As is the case with accident data, though, fatality data cannot be used to draw conclusions about relative vessel safety unless the corresponding exposure and use data is available. For example, Figure 2 shows that each year, the number of PWC fatalities is significantly less than the number of recreational boating fatalities, leading some to conclude that PWC are safer. Alternatively, it also shows that the overall number of boating fatalities has decreased in recent years, while the number of PWC fatalities has increased (NTSB 1998; USCG 1997,1998), which suggests to many that PWC are an increasing public safety threat. However, when compared to sales data from the mid-1990s, the data in Figure 2 show that the increase in PWC fatalities corresponds to the mid-1990s surge in PWC sales and use and that the PWC fatality *rate* (i.e., number of deaths per vessel or number of deaths per hour of operation) has remained rather constant, even though the *number* of PWC fatalities has risen (NTSB 1998). Therefore, these data alone cannot be used to compare the relative safety of PWC and other vessels.

In general, most boating and PWC-related safety incidents can be attributed to operator-controllable factors, with relatively few being due to vessel or environmental factors. Moreover, there is little data or evidence to suggest that PWC are inherently more dangerous than other recreational vessels.

2.2.5 Education and PWC Safety

According to the NTSB, most PWC accidents and fatalities are due to three factors: inattention, inexperience and/or inappropriate use of speed (1998). These factors have little to do with the vessel itself and stem from the fact that PWC riders receive little, if any, training before they embark on the water. Consequently, they are not familiar with navigational rules and regulations, they are not aware of PWC safety precautions and they may behave recklessly and irresponsibly.

To rectify this, boating safety officials are turning to education to enhance the awareness and safety of the boating community. Many states have institutionalized boating operation and safety training classes and several have implemented mandatory education requirements for some or all boaters. Although these requirements usually focus on younger boaters (i.e., children and teenagers) and rental customers, the high-profile controversy surrounding PWC safety and use has prompted many states to mandate education and training for PWC operators of all ages.

In support of these efforts, the PWC industry and its partners have teamed up with local, state and federal officials to advance PWC safety and education throughout the country. For example, the PWIA encourages PWC operators to participate in voluntary education programs and it develops a variety of PWC-specific training materials. Furthermore, it works with state legislators to establish more effective safety regulations and it loans PWC to law enforcement agencies to boost their response and rescue capabilities. Finally, the PWIA actively campaigns to transform the reckless image of PWC users and it lobbies manufacturers to improve the safety of PWC design characteristics (PWIA 2000).

Boating safety assessments suggest that these efforts are paying off. Several states with strong PWC education and safety requirements have significantly reduced their PWC accident and fatality statistics. For example, the year after implementing mandatory PWC education, Minnesota reported one-third fewer PWC collisions than in the previous year. Similarly, in Wisconsin, PWC accidents decreased by 68% in the two years following mandatory PWC education. In Virginia, mandatory education has helped reduce the number of PWC accidents by 40% since 1999 and in California, PWC accidents have dropped 32% since 1998. Finally, despite the fact that PWC registrations have tripled in Connecticut in recent years, the state's number of PWC accidents have steadily decreased since it mandated PWC education in 1992.

2.2.6 Management Considerations

- Most PWC-related safety incidents are linked to inappropriate or irresponsible vessel use, not to the vessel itself.

- It is difficult to ascertain if PWC are a greater safety threat than other vessels because:
    - Incomplete exposure and safety data make it difficult to quantify or compare the relative safety of different vessel types.
    - Distinct differences between boating and PWC-related accidents and fatalities make them difficult to compare.
- PWC manufacturers have addressed design-related safety concerns in various ways:
    - Newer PWC models are larger, heavier and more stable than older models.
    - All new PWC models have safety lanyards and "kill switches" and many now have secondary “off-throttle” steering mechanisms.
- Boating safety assessments suggest that boating education efforts are effectively reducing PWC infractions.

2.3 MARINE ENGINE EMISSIONS

Recreational motorboats emit a variety of air and water pollutants (Table 1). Emission levels depend on engine specifications such as model year, horsepower rating, load factor and system design (Jackivicz and Kuzminski 1972; Juettner *et al.* 1995a), as well as operational characteristics such as vessel speed, hours of use and frequency of tuning (Warrington 1999). Therefore, emission levels vary both within and among vessel types. From a resource management perspective, it would be useful to compare the relative emission levels of different vessel types. This comparison would enable managers to effectively identify and regulate more polluting vessels. Thus far, however, researchers have only been able to accurately compare the relative emissions of different engine types.

Table 1. Pollutants Emitted from Recreational Marine Engines

BTEX	Benzene, Toluene, Ethyl benzene & Xylene
MTBE	Methyl-tertiary-Butyl-Ether
PAHs	Polycyclic aromatic hydrocarbons
CO	Carbon monoxide
NOx	Nitrogen oxides
PM	Particulate matter
SH	Saturated hydrocarbons

2.3.1 Marine Engine Comparisons

Most recreational motorboats, including PWC, utilize carbureted 2-stroke engine technology. Compared to their fuel-injected or 4-stroke counterparts, these engines are relatively inefficient and discharge a significant portion of their fuel intake into the water unburned (CARB 1998; VanMouwerik and Hagemann 1999; Tahoe Regional Planning Agency 1999;

Warrington 1999). Two-strokes also emit a bluish-gray smoky exhaust composed of toxic and smog-forming compounds. Overall, these emissions contribute to the degradation of air and water quality and compromise the integrity of coastal and marine ecosystems by threatening biological resources such as vegetation and wildlife.

In compliance with the U.S. Environmental Protection Agency's Clean Air Act rules, the marine manufacturing industry is addressing many of the concerns surrounding 2-stroke engines by developing cleaner, more efficient models and by improving the performance of traditional engine components. For example, the industry is redesigning piston-top deflectors (to reduce raw fuel throughput) and enhancing exhaust manifolds to decrease the release of airborne hydrocarbons and carbon monoxide. The industry is also using technologies such as direct fuel injection (DFI) systems and catalytic converters to reduce harmful hydrocarbon emissions and improve fuel economy (PWIA 2000). Despite these improvements, DFI-2-stroke engines still have higher emissions levels than 4-stroke engines (Bluewater Network 1998; Gabele and Pyle 2000). Therefore, certain manufacturers are now producing 4-stroke engines for a wider variety of vessels, including PWC and high-performance motorboats. (See Box 1 for more information about 2-stroke and 4-stroke engines.)

Box 1. Two-Stroke vs. Four-Stroke Engines

Two-stroke and 4-stroke engines derive their power in similar ways but they differ widely in their operational efficiency and emission levels. Both engine types burn a mixture of gasoline and air in an airtight cylinder. This combustion results in a buildup of gas pressure that pushes a piston down through the cylinder to create potential energy. In outboard motorboats, the potential energy is then transferred via connecting rods from the cylinder to the driveshaft where it powers a propeller and pushes the watercraft (Kuzminski and Jackvicz 1972). In PWC, the energy is transferred from the cylinder to an impeller that drives a pump and creates a pressured water jet that propels the vessel.

Two-stroke and 4-stroke engines utilize different lubrication methods that affect their overall emissions levels. Four-strokes have a separate lubricating system that minimizes the release of unburned oil into the water but 2-strokes require oil to be added directly into the fuel. The use of this mixture releases more oil, hydrocarbons and particulate matter than pure gasoline and results in a smoky blue exhaust (ENSR 1998).

Two-stroke and 4-strokes also differ in their power generation. Two-stroke engines generate power with every downward piston stroke, which requires them to combine fuel intake and exhaust into one stroke and fuel compression and ignition into the other stroke (Kuzminski and Jackivicz 1972). This combination creates power with every downward stroke but it allows significant amounts of unburned fuel to pass through the cylinder and into adjacent surface waters. Although 2-strokes frequently use deflectors to direct fuel away from the exhaust manifold, excessive throughput still occurs (Kuzminski and Jackivicz 1972). Therefore, marine manufacturers are beginning to outfit 2-stroke engines with direct fuel injection (DFI) systems such as the Ficht or Orbital.

DFI systems decrease fuel waste by injecting the gasoline-oil mixture directly into the cylinder after the exhaust port has closed. The Ficht system uses a tiny hammer-like part to force each injection spray into the combustion chamber. This creates smaller fuel drops, which evaporate more quickly for combustion. The Orbital system mixes gas and oxygen and then blasts the mixture into the combustion chamber at timed intervals. DFI systems use about half as much oil and have about 70% lower emission levels than older 2-stroke models. Generally speaking, however, DFI-2-stroke engines still have higher emission levels than 4-stroke engines (Gabele and Pyle 2000).

Four-stroke engines effectively minimize fuel throughput by performing fuel intake and exhaust on different strokes. Consequently, they can only generate power on alternate down-strokes and offer a lower range of power than 2-stroke engines (Kuzminski and Jackivicz 1972). Four-stroke engines also tend to be larger and heavier than 2-stroke engines, making them less desirable to some consumers. However, the demand for more fuel-efficient and environmentally friendly vessels is currently driving the development of 4-stroke engines that are smaller, lighter and more powerful and that can be used on a wider variety of vessels, including PWC.

2.3.2 Water Quality Impacts

There is some concern regarding the release of oil by recreational motorboats, particularly with older vessels that drain excessive fuel from the crankcase directly into the water. However, vessels manufactured since 1972 usually have scavenging devices that recycle the lost fuel and reduce oil throughput. Therefore, with regard to boating-related emissions, most researchers are concerned about the release of BTEX compounds (the primary constituents of gasoline), MTBE (a combustion-enhancing fuel additive) and PAHs.

Several studies suggest a correlation between BTEX, MTBE and PAH field concentrations and motorized recreational vessel use. These concentrations often increase throughout the summer boating season (May to September), with distinct spikes occurring after peak boating dates such as the Fourth of July and Labor Day (Allen *et al.* 1998; Allen and Reuter 1999; Miller and Fiore 1997; Oris *et al.* 1998; Reuter *et al.* 1998). These tend to diminish within weeks or months after the boating season and, given our present understanding of aquatic ecosystems, do not appear to significantly degrade overall water quality (Revelt 1994; Warrington 1999). However, BTEX compounds, MTBE and PAHs have been linked to acute and chronic toxicity in fish (Balk *et al.* 1994; Juettner *et al.* 1995; Tjaernlund *et* al. 1995, 1996) and may adversely affect fish growth and zooplankton survival and reproduction (Oris *et al.* 1998). Moreover, they may impact the surface microlayers found at the air-water and sediment-water interfaces. These ecologically vital layers support bacterial colonies that influence aquatic nutrient levels and sustain the planktonic and larval communities necessary to uphold aquatic ecosystems. They also serve as a spawning ground for many sport fish. Therefore, surface microlayers may be vulnerable to small and/or temporary increases in recreational boating-related pollutants (Warrington 1999; Von Westerhagen *et al.* 1987).

In general, BTEX compounds and MTBE are usually discharged with unburned fuel, while PAHs are exhausted following fuel combustion (VanMouwerik and Hagemann 1999). Once released, these pollutants react very differently in the water column and give rise to separate ecological concerns.

BTEX Compounds

BTEX compounds are single-ringed (monoaromatic) hydrocarbons that make up a significant portion of petroleum products such as gasoline and motor oil. They have a small size, low molecular weight and are highly soluble. They are also extremely volatile and, once released, they do not remain in the water for long because they quickly diffuse to either the air-water interface, where they evaporate, or to the water-sediment interface, where they become trapped in the sediments. Any remaining traces of BTEX compounds are usually broken down by biological degradation (Christensen and Elton 1996; Warrington 1999). Extreme levels of BTEX compounds are toxic to aquatic organisms but their short residence times tend to keep BTEX field concentrations orders of magnitude below established toxicity thresholds.

Most BTEX-contamination can be linked to leaky underground storage tanks and/or stormwater runoff (Christensen and Elton 1996), but the public has become increasingly concerned about the release of BTEX compounds from recreational motorboats. Studies suggest that current levels of boating-related BTEX emissions are not a major threat to marine environments (Allen *et al.* 1998; ENSR 1998; Revelt 1994), especially when compared to landside urban or industrial sources. However, it should be noted that areas with high petroleum background concentrations (i.e., harbors, marinas or industrial sites) may already exhibit BTEX toxicity and may be more sensitive to boating-related BTEX emissions.

Methyl Tertiary-Butyl-Ether

MTBE is a hydrophilic, organic compound that is added to gasoline to increase burning efficiency and improve engine performance (US EPA 1997, 2000). Although MTBE-use has been linked to air quality improvements in regions plagued by smog, researchers are concerned that MTBE use may threaten water quality (Reuter *et al.* 1998). Those areas using MTBE-enhanced gasoline usually observe elevated levels of MTBE in their fresh and/or marine waters. Most of this MTBE comes from automobile exhaust, stormwater runoff and leaky storage tanks but studies suggest that some MTBE contamination may be attributed to marine engine exhaust (Allen *et al.* 1998; Allen and Reuter 1999; Reuter *et al.* 1998).

Evaporation at the air-water interface is a primary mechanism for MTBE removal from surface waters (Miller and Fiore 1997; Reuter *et al.* 1998), but, due to its high solubility and small molecular size, most MTBE diffuses away from the surface before significant loss occurs. Consequently, MTBE tends to remain in solution and, in shallow-water systems, can rapidly penetrate groundwater supplies. Moreover, MTBE is not biodegradable, it does not react to UV light and it rarely adsorbs to suspended particulate matter (Tahoe Research Group 1997). This resistance to natural breakdown enables MTBE to build up in aquatic areas. Fortunately, preliminary research suggests that microbial communities may have the potential to mineralize MTBE, thereby removing significant quantities of it from the water column and/or sediments (Bradley *et al.* In Press).

At extremely high concentrations, MTBE may be acutely and/or chronically toxic to aquatic organisms (Werner and Hinton 1998). Adverse effects include the onset of cancer and disruptions to the renal, reproductive and nervous systems. However, ambient field concentrations are several orders of magnitude below toxicity thresholds and MTBE has not been shown to bioaccumulate in the food chain (Tahoe Research Group 1997). Therefore, it poses little or no threat to fish and wildlife and is not considered to be a major issue in marine ecosystems. (See Box 2 for more information about MTBE and drinking water).

Box 2. MTBE and Drinking Water

Methyl-tertiary-butyl-ether (MTBE) is an oxygenate that is added to gasoline to facilitate combustion and enhance engine performance. MTBE production and use has increased significantly since 1990, when Congress amended the Clean Air Act (CAA) and mandated the use of oxygenated, or "reformulated," gasoline (RFG) in regions with significant air quality problems (Tahoe Research Group 1997; US EPA 1997). In general, reformulated gasoline improves air quality by reducing the amount of toxic and/or smog-forming hydrocarbons that engines typically exhaust (US EPA 1995, 2000).

Several oxygenates are available for RFG production but most manufacturers favor MTBE because it is cost efficient and blends well. Recent reports claim that MTBE is used in over 80% of RFG supplies and that the U.S. currently produces over 200,000 barrels of MTBE each day (US EPA 2000).

Although toxic and smog-forming air emissions have decreased with the addition of MTBE to gasoline, research suggests that these air quality benefits are occurring at the expense of drinking water quality. MTBE has an unpleasant taste and odor that degrades the integrity of freshwater drinking supplies. Therefore, the EPA has established an MTBE Drinking Water Advisory Range of 20-40 micrograms per liter. This range is based strictly on taste and odor considerations and does not address potential threats to human health (US EPA 1997).

MTBE-related health concerns stem from the fact that MTBE is classified as a potential human carcinogen. However, laboratory studies show that toxic and cancerous effects require extraordinarily high concentrations or exposure levels. Since humans are indisposed to drinking water contaminated with even low MTBE concentrations (<20-40 micrograms per liter), it is unlikely that direct MTBE consumption poses a threat to human health. Nonetheless, the EPA has established a highly conservative MTBE safety threshold of 70 micrograms per liter (US EPA 1997). It has also begun to phase out MTBE use throughout the country.

Polycyclic Aromatic Hydrocarbons

PAHs are organic compounds composed of two or more fused carbon-ring structures (Albers 1995). Smaller PAHs (2-3 rings) are usually found in the gas phase and are more soluble than larger PAHs (4-7 rings), which are found in the solid phase (Albers 1995; Marr *et al*. 1999). When emitted into the water column, smaller PAHs readily evaporate or dissolve but larger PAHs tend to sink into the sediments (ENSR 1998). At the same time, all PAHs adsorb to organic material, which transports them throughout the water column and into the sediments. Adsorption also enables aquatic organisms to ingest PAHs, which introduces these toxins into the marine food web (Albers 1995; Eisler 1987).

Elevated PAH concentrations can be acutely or chronically toxic to fish and other aquatic organisms (Baumann 1989). These organisms are initially affected at the subcellular level when PAHs bind to DNA and cellular proteins. This inhibits biochemical processes and causes extensive cellular damage. More severe damage is manifested as mutations form in the liver and kidneys and malfunctions occur in the circulatory and nervous systems (Albers 1995). Laboratory studies also suggest that high concentrations of PAHs may cause cancer in fish but inadequate field studies weaken the case for a casual linkage between the two (Baumann 1989; Eisler 1987; Neff 1985).

As with other emission-related pollutants, surface water PAH-concentrations are usually significantly lower than toxicity thresholds (Albers 1995, 2000). This is due, in part, to the predominant use of 2-stroke engines, which primarily exhaust PAHs that are smaller, lighter and more evaporative. However, PAH levels may be significantly higher in sediment beds (Albers 2000; ENSR 1998) and areas with ample sediment suspension are often subject to long-term PAH contamination. Studies indicate that sediments are usually contaminated by the larger, heavier PAHs that are more prevalent in 4-stroke exhaust. Consequently, with regard to PAHs, the proposal to switch from 2-stroke to 4-stroke engines in order to preserve water quality may be problematic. Other studies suggest that exposure to ultraviolet light greatly increases PAH toxicity (Oris *et al*. 1998), thereby questioning whether or not PAH emissions reductions can adequately protect shallow-water organisms from lethal and/or sub-lethal photo-dynamic effects.

Similarly to BTEX compounds and MTBE, however, marine engine exhaust is a relatively minor contributor to overall PAH emissions. Hundreds of PAHs are produced from a wide array of sources including automobiles, trucks, buses, power plants, wood stoves, burning leaves and forest fires (Albers 1995). Recreational boating levels are rarely high enough to cause significant exhaust-related environmental impacts but they may exacerbate existing PAH contamination near urban or industrial sites (ENSR 1998).

2.3.3 Air Quality Impacts

The U.S. Environmental Protection Agency (EPA) has been regulating highway vehicle emissions since the 1970s; however, it only recently began addressing nonroad or off-highway sources of air pollution. These sources account for about 10% of all hydrocarbon emissions and regulating them is necessary if states are to comply with the National Ambient

Air Quality Standards (NAAQS). In accordance with the 1990 Clean Air Act (CAA) Amendments, the EPA now monitors and regulates an array of nonroad pollution sources such as lawn and garden equipment, construction and farm equipment, recreational all-terrain vehicles and marine vessels (US EPA 1999).

Through studies mandated in 1990, the EPA has concluded that the gasoline-powered engines found on motorboats, jetboats and PWC comprise about 30% of all nonroad emissions. Furthermore, in areas with extensive boating populations, marine engines alone can account for 10% of all hydrocarbon emissions. Consequently, in 1996, the EPA established new air emission standards for all gasoline-powered marine engines. These standards are being phased in from 1998-2006 and should reduce the hydrocarbon emissions of these engines by 75% in 2025 (US EPA 1996). In addition to these federal standards, the California Air Resources Board (CARB) has adopted a more stringent set of regulations to address that state's massive boating population and extreme air quality problems. CARB requires marine engine manufacturers to reduce their hydrocarbon emissions by 75% on 2001 models and by 90% on 2008 models (CARB 1998). Neither the EPA nor the CARB standards apply to engine models pre-dating the restrictions.

Both sets of standards enable manufacturers to average emissions reductions across their entire range of engines, thereby providing them the flexibility to develop their technological solutions based on competitive market demand (US EPA 1996). In other words, manufacturers can select which engines to improve based on vessel sales and/or consumer expectations. As a result, they have been able to respond to demands for cleaner PWC by enhancing PWC engine performance (i.e., ignition, acceleration and maneuverability) and reducing smoke, fumes and noise.

Finally, it is worth noting that marine engine exhaust also contains high levels of nitrous oxides (NOx), carbon monoxide (CO) and particulate matter (PM) (Gabele and Pyle 2000; Kado *et al.* 2000). NOx affects human pulmonary and respiratory health, CO contributes to ground level ozone and certain PM-associated pollutants are genotoxic, or DNA-damaging, to aquatic organisms (Warrington 1999). Although the current marine engine regulations mandate small reductions in NOx, they do not address CO or PM emissions. Since these compounds are easily channeled back into the water column, more research should be conducted to determine if these compounds should be regulated.

2.3.4 PWC and Emissions

Recently, public concern regarding recreational vessel emissions has focused on PWC. PWC, with their higher power ratings and load factors, are widely perceived to have disproportionately high emission rates (relative to other motorized vessels). These characteristics are hypothesized to cause PWC to burn fuel more quickly than other vessels, thereby creating higher emissions (Bluewater Network 1998; NPCA 1998). However, researchers have not been able to accurately quantify how much gasoline or exhaust is being emitted from specific vessels (Miller and Fiore 1997; ENSR 1998) or to determine how vessel emissions vary under conditions of actual use (Allen *et al.* 1998).

PWC are also singled out because of their ability to access shallow-water areas. Presumably, this enables PWC to contaminate waters that were previously immune to recreational boating exposure. However, researchers have found it difficult to link contaminated water samples to a specific source (ENSR 1998) and they have yet to quantify the input of PWC-related emissions to shallow-water areas.

Although the current data are inconclusive, research regarding PWC emissions levels and impacts, these vessels continue to be targeted by citizen and environmental groups concerned about recreational boating and water quality. Therefore, the PWC industry is taking steps to ensure that its products are meeting or exceeding current environmental standards. Newly designed models using technologies such as catalytic converters and DFI-equipped 2-stroke engines retain the light weight and premium performance of standard 2-stroke engines, while offering consumers advantages such as instant no-smoke starting, enhanced throttle response, reduced exhaust emissions and increased fuel efficiency (PWIA 2000).

2.3.5 Management Considerations

- Although motorboats and PWC do emit a variety of toxic pollutants, their overall environmental impact is usually much smaller than that of other pollution sources such as marinas or residential, commercial and industrial shoreline developments.

- Most of the engine emission levels reported in the literature are derived from studies conducted in the early 1970s. Given the advances in marine engine technology and the changes in fuel composition over the past few decades, estimates derived from these studies may not accurately reflect the emission levels of newer marine engines.

- The water quality impacts widely attributed to PWC use can also be linked to other vessels that utilize carbureted 2-stroke engine technology.

    - Although comparing PWC emissions to those of other motorboats would be useful, it is usually only possible to compare the relative emission levels of different engine types.

    - Until more conclusive evidence is available to determine the relative emissions levels of different vessel types, management efforts to regulate marine engine emissions should reflect the same standards for all motorized vessels.

- The PWC industry is compliant with current EPA marine emission standards. In addition, most PWC models manufactured since 1998 meet the EPA's 2006 requirements.

- Site-specific exposure and use data is necessary to determine the relative impact of the different vessels in a given body of water. Therefore, the following points should be measured and evaluated:

  - The relative exposure (use) rates of different vessel types.

  - The relative emission rates of different engine and vessel types.

  - The relative solubility, transfer and fate of exhausted pollutants.

  - The potential risk of these pollutants to human health, aquatic life and water quality.

- While gathering this data, it is important to keep in mind that:

  - There is insufficient evidence to verify that PWC--with their higher load factors and horsepower ratings--burn more fuel than other vessels.

  - In many places, PWC use and/or exposure time is significantly lower than that of other motorized vessels.

- Public education is needed to inform operators about water quality issues and stricter law enforcement is required to keep motorized vessels out of sensitive aquatic areas.

- Researchers need to address the following data gaps and scientific uncertainties:

  - The amount of toxic pollutants emitted by different vessels and engine types.

  - The effect of toxic pollutants on overall air and water quality.

  - The effectiveness of regulations that restrict PWC use in shallow-water areas.

2.4 WILDLIFE

Recreational boating generates noise, pollution and physical damage that can threaten coastal and marine wildlife. Box 3 lists a variety of impacts that directly or indirectly affect fish, waterbirds and marine mammals (Meehan 2000; Snow 1989). These impacts vary widely depending on the species at hand and the type/operation of the vessel in use, but they typically entail behavioral disruptions, ecological changes and/or health threats.

Box 3. Wildlife Impacts Linked to Recreational Boating

IMPACT	EXAMPLE
Alarm or flight	*Nest Flushing; Rookery evacuation*
Avoidance or displacement	*Nest abandonment; Migration disruption*
Behavioral alteration	*Decreased foraging or feeding*
Community alteration	*Increased predation (following nest desertion)*
Habitat loss	*Sea grass destruction; Shoreline erosion*
Injury or death	*Vessel collisions; Sediment-related gill damage*
Reproductive failure	*Decreased mating; Increased egg mortality*

Occurrences of these boating-related impacts are well documented but little is known about their cumulative effect. Furthermore, few studies effectively compare the relative impact of different types of recreational vessels and/or activities. Therefore, it is difficult to develop boating management strategies that effectively minimize wildlife disturbance.

2.4.1 PWC and Wildlife

PWC have extensive shallow-water capabilities that enable them to access sensitive aquatic and near-shore habitats. This generates concern because most PWC use occurs during the spring and summer months and coincides with critical wildlife phases such as spawning, mating and nesting (Bluewater Network 1998; Martin 1999; NPCA 1999). Therefore, PWC have the potential to cause adverse wildlife impacts by interfering with feeding, foraging, mating, migration, nesting and reproduction (Burger 1998; Lelli and Harris 2001; Mikola *et al.* 1994; Pfister *et al.* 1992; Rodgers 1995; Rodgers and Smith 1997). PWC also have the to potential to physically damage or chemically pollute shallow-water wildlife habitats (Ballestero 1990; Balk *et al.* 1994; Tjaernlund *et al.* 1995,1996; Snow 1989; Warrington 1999). These concerns are not unique to PWC, however. Non-motorized vessels also have extensive shallow-water accessibility and are widely linked to both wildlife disturbance and habitat damage. Outboard motorboats are equipped with the same engines as PWC and have similar types and magnitudes of toxic emissions. They are also just as capable (if not more) of churning up benthic habitats and are more likely to damage seagrass beds (Ballestero 1990; Snow 1989). Many conventional motorboats are also being equipped with technologies that enable them to access extremely shallow areas. These technologies include electric tilt mechanisms (which raise outboard motors out of the water), jack-plates (which lift propellers onto boat transoms) and jet-feet (which replace propellers with impellers).
In general, there is an overwhelming lack of scientific research regarding PWC-related wildlife impacts. Recent reports summarize extensive anecdotal information put forth by professional wildlife scientists and resource managers. Until more conclusive studies are conducted, however, it cannot be established if PWC threaten wildlife more than other recreational vessels.

Birds

Coastal waterbird populations are susceptible to disturbance by recreational boating, especially during critical mating, nesting and resting periods (Burger 1998; Mikola *et al.* 1994). Therefore, resource managers frequently restrict the use of recreational vessels in or near coastal habitat areas. In response to rising public concerns, many restrictions now target PWC use, but scientific information on the impacts of different vessel types on waterbirds is sparse.

Only a few studies compare the impacts of specific vessel types and these studies lack consensus on whether or not PWC are more detrimental to wildlife than other recreational vessels. One study examines the flushing responses of a single population of colonial nesting birds (Common Terns) at a site in New Jersey. It reports that PWC elicit stronger and more variable responses than outboard motorboats and that Common Tern flushing responses increase as PWC approach at closer distances or faster speeds (Burger 1998).

Conversely, a study of numerous waterbird populations throughout coastal Florida concludes that most waterbird species react similarly to PWC and outboard motorboats. Data from this study reveal that, of 23 waterbird species, 11 react the same to all motorized vessels, 4 react more strongly to outboard motorboats and only one reacts more strongly to PWC (Rodgers and Smith 1997). In addition, several studies beyond the scope of this review link non-motorized vessels such as sailboats, kayaks and canoes to coastal waterbirds disturbance.

Such contradictory evidence makes it difficult to effectively manage recreational boating impacts. Further analysis is necessary to determine the vulnerability of different bird species to various disturbances and to determine the relative disturbance caused by different vessel types. For example, both motorboats and PWC disturb birds breeding during peak boating season, but motorboats often disturb birds feeding or loafing during the colder periods when PWC are rarely used. Therefore, researchers should examine the temporal relationship between boating activity and waterbird activities to determine if short-term or seasonal restrictions should be implemented.

In the meantime, managers can minimize the disturbances caused by recreational boating by establishing conservative speed limits and setback distances for all vessels, particularly motorized ones. Researchers from Florida suggest that a uniform buffer zone of 180m (540ft) can be developed for all recreational vessels. This distance is based on species-specific setback distances of 180m for wading birds, 150m for ospreys, 140m for terns and gulls and 100m for plovers and sandpipers (Rodgers and Schwikert *In Press*). These findings are consistent with earlier research conducted in North Carolina and Virginia that suggested a setback distance of 200m for wading birds (Erwin 1989).

Marine Mammals

Recreational boating activity has been shown to affect various marine mammal species (Dornbusch & Company 1994; Evans 1991; Green 1991; US Department of Commerce 1990). For example, boating traffic frequently flushes harbor seals from the haul-out sites they use to rest, sleep, molt, nurse and give birth (Allen *et al.* 1984; Calambokidis *et al.* 1991; Lelli and Harris 2001; Mortenson *et al.* 2000; Suryan and Harvey 1999). Flushing from these sites disrupts normal rest and/or social interactions and separates pups from their mothers (potentially subjecting them to injury or predation and reducing the overall population size). Harbor seals are more likely to return, or rehaul, to these sites if disturbances are of short duration; therefore, high levels of boating traffic or prolonged vessel use may act as a continuous disturbance and prevent rehauling (Allen *et al.* 1984). Despite concerns regarding PWC use, several studies indicate that harbor seals tend to react more strongly to paddled vessels than to motorized ones (Calambokidis *et al.* 1991; Lelli and Harris 2001; Suryan and Harvey 1999).

Marine wildlife managers are also concerned that PWC may interfere with the daily activities of cetaceans and other marine mammals. A study linking jetboat-based parasailing to the interference of feeding and migration in humpback whales (Green 1991) prompted the state of Hawaii to classify PWC as "thrillcraft" and prohibit their use in certain areas during the peak whale season, December 15-May 15 (Bluewater Network 1998; NPCA 1998). Others suggest that marine mammals such as manatees or porpoises may be at risk of collision with PWC but there is no evidence to support this suggestion. In fact, the Florida Fish and Wildlife Conservation Commission has issued a special letter assuring concerned citizens that there has never been a PWC-related manatee death in Florida.

In general, most concerns regarding PWC and marine mammals stem from the audio-visual disturbances these vessels create. There is no scientific evidence to support these claims, but a wide range of anecdotal information is available. Many environmental groups, researchers and wildlife managers maintain that the acoustic qualities, high speeds and operational characteristics of PWC pose a greater threat to wildlife than other vessels. Some state that marine mammals have difficulty adapting to the erratic maneuverability and variable noise of PWC (Bluewater Network 1998; Gentry 1996; Martin 1999; NPCA 1999; San Juan County Planning Department 1998), while others suggest that prolonged PWC use makes it difficult for marine mammals to find safe escape routes and breathing spots (Gentry 1996). Others contend that, since PWC are essentially mute in the pelagic realm, they may be more likely to startle marine mammals (San Juan County Planning Department 1998).

Until more conclusive evidence is available, resource managers can effectively reduce marine mammal disturbances by using buffer zones, setback distances and zoning to keep recreational vessels away from critical marine mammal habitats.

Fish and Invertebrates

Recreational boating can adversely impact marine fish and invertebrate species. These impacts are most pronounced in shallow-water areas and are compounded by the fact that peak boating times usually coincide with the critical life stages of these species.

For example, outboard motorboats and PWC generate tremendous engine wash that can damage benthic eggs and larvae. Direct damage occurs as shear and rotational forces destroy fragile organisms (Stolpe 1992) and indirect damage occurs as organisms are smothered or buried by sediments kicked up by passing vessels (Morgan *et al.* 1983; Newcombe and MacDonald 1991).

Marine fish and invertebrates are also vulnerable to a variety of impacts linked to marine engine emissions. These emissions can increase egg mortality by contributing to shell thinning or they can decrease larval settlement rates by chemically altering the benthic substrate (Von Westerhagen *et al.* 1987). Moreover, many of these emissions have been found to be toxic to all life stages of fish and invertebrates (egg, larvae, juvenile and adult). More specifically, combusted hydrocarbons have been linked to an array of toxic side effects including sub-cellular mutations, biological systems damage and, in extreme cases, cancer. These effects, in turn, disrupt bodily functions such as growth, reproduction, respiration, circulation, osmoregulation and metabolism (Balk *et al.* 1994; Tjaernlund *et al.* 1995, 1996).

In general, ambient hydrocarbon concentrations are usually significantly lower than established toxicity thresholds and, in most areas, recreational boating-related pollution is not considered to be a major threat to marine organisms. However, studies show that toxicity levels may be elevated in shallow water areas due to 1) insufficient hydrological flushing (Warrington 1999) or 2) photo-dynamic magnification by ultraviolet light (Oris *et al.*

1998). Furthermore, preliminary research suggests that even marginal or short-term increases in hydrocarbon concentration may adversely impact organisms living in sea-surface microlayers (Von Westerhagen *et al.* 1987; Warrington 1999).

Researchers are beginning to question the ecological impacts that recreational boating may have on marine fish and invertebrate species. They are currently examining whether or not boating-related traffic and noise disrupts foraging, migration or schooling behavior or alters predator-prey relationships. No data have been published and there is no evidence to suggest that PWC are a more viable threat than other motorized vessels. In the meantime, managers can minimize potential impacts to marine fish and invertebrates by restricting all motorized vessel use in sensitive shallow-water habitat areas.

2.4.2 Management Considerations

- Recreational boating has been linked to noise, pollution and physical damage that adversely affects wildlife species and populations. However, it should be noted that:
    - Most wildlife disturbance is due to inappropriate or irresponsible operator behavior, rather than to the actual vessel itself.
    - Very few studies specifically examine PWC-related wildlife impacts and there is no consensus on whether or not PWC disturb wildlife more than other vessels.
    - Specific vessel and/or activity restrictions may be required in extremely shallow or near-shore areas.
- With regard to PWC, wildlife experts are predominantly concerned about their noise impacts and their ability to access shallow-water areas (but they note that neither of these is unique to PWC). Appropriate management strategies include:
    - Establishing buffer zones and setback distances to keep PWC and other vessels away from sensitive, shallow-water habitat areas and to reduce PWC noise levels.
    - Implementing preliminary mitigation strategies such as spatial/temporal zoning or operational restrictions to minimize potential disturbances.
- Essential and/or sensitive habitat areas should be identified and prioritized during PWC management efforts. For example:
    - PWC use should be restricted near waterbird breeding and foraging areas.
    - Resting or loafing sites along migration routes should be targeted for protection.
- More research is necessary to quantify the release of PWC-related pollutants and to determine the biological impact of these substances on aquatic organisms.

- Researchers should address the following data gaps and scientific uncertainties:

  - Wildlife responses to different vessel types and approaches and how these responses differ by species or change over time (i.e., daily, seasonally, annually).
  - The effects of vessel noise on wildlife activities such as feeding, foraging, loafing, mating, migrating, nesting and spawning.

  - The effectiveness of set-back distances, buffer zones and no-use areas as wildlife protection mechanisms.

  - The relative habitat damage caused by different vessel types.

  - The amount of toxic pollutants released by outboard motorboats and PWC and the biological impact of these substances on aquatic organisms.

2.5 SUBMERGED AQUATIC VEGETATION (SAV)

Underwater plants and algae, known collectively as submerged aquatic vegetation (SAV), are vital to aquatic ecosystems and their inhabitants. Although SAV refers to many vegetation types, this report focuses on seagrasses, which are subtidal marine plants that form dense beds in coastal estuaries. They are usually substrate-bound and their productivity is limited by the attenuation of light through the water column (Athanas no date). Since seagrasses exist exclusively in shallow-water areas, they are highly vulnerable to the impacts of recreational boating.

Seagrasses perform a variety of functions that contribute to estuarine health and productivity. For example, they stabilize estuarine substrates by trapping sediments in their fibrous, lateral rhizome systems. Furthermore, they protect and nourish estuaries by dampening hydrologic movement and filtering dissolved nutrients with their long, blade-like leaves (Short and Short 1984). Seagrasses also diversify breeding and nursery grounds for aquatic organisms and provide food and shelter to fish, shellfish and waterbirds (Phillips 1984; Thayer *et al.* 1984).

Seagrass communities are diminishing throughout the world. Seagrass declines are due primarily to pollution and disease (Short *et al.* 1987, 1989, 1993), but they may be exacerbated by human activities in the coastal zone. Many of these activities, such as residential or commercial development, occur on land but some relate to recreational boating and water use (Short *et al.* 1991). Examples include dock and pier construction, sewage discharge, anchor/mooring deployment, propeller scarring and vessel grounding.

2.5.1 Direct Impacts

The vessels and activities affiliated with recreational boating can harm seagrass either directly or indirectly (Ballestero 1990). Direct impacts usually occur when vessels contact and injure plant structures (Short *et al.* 1991). Common scenarios include:

- Boat hulls striking the sediment bed and destroying root systems.
- Propellers slashing rhizomes and leaf blades.
- Propulsion and/or hull pressure eroding roots and rhizomes.
- Vessel-induced waves and wakes causing shoreline vegetation erosion.

These occurrences result in bare patches or "scars" in seagrass beds and often cause extensive damage to seagrass communities (Dusek and Battle 1998).

PWC are widely perceived to scar nearshore and intertidal seagrass beds but researchers in New Hampsire and the Florida Keys found no significant PWC-related damage after subjecting test beds to extensive PWC use (Anderson 2000; Continental Shelf Associates 1997). In general, PWC-related SAV impacts are reduced by design characteristics such as shallow drafts, impellers and horizontally oriented jet propulsion systems. Moreover, they do not perform well in seagrass beds or extremely shallow waters areas. When PWC are operated in less than the manufacturer-recommended depth of 2 feet, their intake grates clog with suspended sediments and vegetative debris, causing their engines to overheat (Ballestero 1990). To avoid permanent engine damage, an operator must turn the PWC off, dismount the vessel, manually clear the grate and resume operation in a deeper, more appropriate area. By comparison, when an outboard propeller becomes clogged with vegetative debris, the operator needs only to stop, reverse the vessel (which rotates the propeller in the opposite direction and unwraps the vegetation), clear the vegetative debris and proceed through the seagrass bed.

Finally, PWC-related SAV damage is usually minor compared to the seagrass scarring and shallow water habitat damage caused by more traditional vessels. For example, studies indicate that conventional outboard motorboats are the principal cause of SAV damage (Dusek and Battle 1998; Snow 1989) and these vessels have been linked to extensive seagrass scarring in Florida, Maryland and elsewhere (Naylor 2000; Smith 2000). Non-motorized craft such as canoes and kayaks can also damage SAV, especially when inexperienced boaters use their oars and paddles to dislodge or maneuver their vessels in shallow water areas. Restricting recreational vessel use to appropriately deeper waters can effectively reduce most of these direct impacts.

2.5.2 Indirect Impacts

Indirect impacts usually occur when recreational boating impedes primary productivity (photosynthesis). As mentioned above, seagrass productivity is limited by the amount of light that passes through the water column to leaves. Dock and mooring facilities often shade surrounding waters and decrease photosynthesis by inhibiting the passage of light through the water column (Ross 1985). Photosynthesis may also be affected if algal blooms form in the water column and shade the plants below. Studies suggest that boating-related nutrient releases contribute to algal blooms, but these sources are usually insignificant compared to land-side sources such as septic systems or stormwater runoff (Short *et al.* 1989; 1991).

Seagrass health and productivity may also be compromised if sediments are disturbed by vessel waves and wakes. For example, suspension-induced turbidity may decrease light penetration enough to inhibit photosynthesis (Short *et al.* 1989; Stolpe 1992) or resettling particles may temporarily smother the photosynthetic receptors found on plant surfaces. These impacts are a function of sediment particle size, with greater disturbance occurring in systems with smaller, finer particles than in systems with larger, coarser particles (Stolpe 1992).

Although research indicates a correlation between boating activity and short-term turbidity levels (Anderson 2000; Koch 2000), there is little evidence to show that boating-related turbidity chronically decreases photosynthesis. This is primarily due to the fact that natural turbidity sources (i.e., wind or wave activity) usually outweigh vessel-induced turbidity (Koch 2000). However, it may also be due to the fact that most studies only examine the effect of single vessels travelling along single-pass transects. These studies quantify the amount of sediment suspension (and subsequent resettlement) affiliated with a single vessel but they neglect the cumulative impacts that arise when multiple vessels circle about in the same area for a prolonged period of time. Multiple vessel studies are necessary to determine the relative impact of different vessel types and to compare the impact of boating-related sediment disturbance to natural causes of turbidity such as wind, waves and runoff.

Although few studies have effectively compared PWC-related sediment disturbances to those of other motorized vessels, inferences can be made based on correlation between wave-/wake-size and subsequent erosion or resuspension rates. In general, sediment disturbance tends to increase with wave-/wake-size and vessel-generated wave-/wake-sizes tend to increase with hull length, vessel weight, draft depth, power rating and operational speed. Therefore, PWC—with their light hulls and shallow drafts—should create smaller waves and cause less sediment disturbance than larger motorboats. Furthermore, when operated at moderate to high speeds, PWC tend to plane across the surface of the water, which also reduces their wave size and ability to disturb sediments. Studies evaluating PWC use in seagrass beds report no significant difference between PWC-induced sediment suspension and that caused by other outboard motorboats (Anderson 2000) and show that, when operated according to manufacturer recommendations, PWC do not significantly affect erosion rates or ambient turbidity levels (Continental Shelf Associates 1997).

However, PWC are frequently operated in ways that enhance their capacity to damage seagrass communities. For example, PWC are often used in shallow water areas, where their jet wash is more likely to kick up sediments. PWC also tend to kick up more sediment when operators are performing acrobatic maneuvers, traveling at slower speeds or rapidly accelerating. These activities tilt PWC back into the water column and direct their jet wash downward into underlying sediments and seagrass beds. PWC-related seagrass damage may also be exacerbated if PWC operation is spatially and/or temporally concentrated. Multiple PWC circling about in that same vicinity may have a greater impact than a single PWC traveling through the same area.

No broad generalizations can be made about PWC-related SAV damage. To determine the capacity of PWC to disturb sediments and damage SAV, managers need to complete site-specific analyses that examine PWC use characteristics in the context of specific physical parameters such as water depth, sediment size and ambient turbidity. In the meantime, restricting outboard motorboat and PWC use from shallow water areas will effectively minimize these indirect impacts.

2.5.3 Management Considerations

- With regard to direct SAV impacts (i.e., seagrass scarring, rhizome slashing, substrate erosion, etc.), research suggests that PWC-related damage is less significant than the damage caused by propeller-driven vessels. In addition, design characteristics such as shallow drafts, impellers and horizontally oriented jet propulsion systems, make PWC use relatively benign in SAV communities.

- With regard to indirect SAV impacts (i.e., decreased primary productivity), very few studies specifically examine PWC-related damage and how it compares to propeller-driven vessel damage.

  - Since PWC create smaller wakes and waves than other motorized vessels, they may cause less indirect SAV damage.

  - Certain operational behaviors (i.e., shallow-water operation, concentrated use, acrobatic maneuvers, etc.) increase the potential for PWC-related impacts in sensitive SAV communities.

- Channel markers and/or tide gauges are useful tools for directing PWC use away from SAV beds and other sensitive shallow-water areas.

- Site-specific analyses that examine PWC use characteristics in the context of local physical parameters are necessary to determine the capacity for PWC to damage SAV.

- Researchers should address the following data gaps and scientific uncertainties:

  - The amount of sediment suspension and turbidity attributed to vessel use and how it varies with vessel type or operation, water depth and sediment characteristics.

  - The effect of vessel-induced sediment suspension and turbidity on biological factors such as primary production rates, SAV health and habitat quality.

  - The effectiveness of updated navigational charts and markers at restricting vessel-use in shallow water areas that are subject to erosion and/or turbidity impacts.

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